DOSE ASSESSMENT ACTIVITIES IN THE REPUBLIC OF THE MARSHALL ISLANDS

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Abstract—Dose assessments, both retrospective and prospective, comprise one important function of a radiological study commissioned by the Republic of the Marshall Islands (RMI) government in late 1989. Estimating past or future exposure requires the synthesis of information from historical data, results from a recently completed field monitoring program, laboratory measurements, and some experimental studies. Most of the activities in the RMI to date have emphasized a pragmatic rather than theoretical approach. In particular, most of the recent effort has been expended on conducting an independent radiological monitoring program to determine the degree of deposition and the geographical extent of weapons test fallout over the nation. Contamination levels on 70% of the land mass of the Marshall Islands were unknown prior to 1994. The environmental radioactivity data play an integral role in both retrospective and prospective assessments. One recent use of dose assessment has been to interpret environmental measurements of radioactivity into annual doses that might be expected at every atoll. A second use for dose assessment has been to determine compliance with a dose action level for the rehabitation of Rongelap Island. Careful examination of exposure pathways relevant to the island lifestyle has been necessary to accommodate these purposes. Examples of specific issues studied include defining traditional island diets as well as current day variations, sources of drinking water, uses of tropical plants including those consumed for food and for medicinal purposes, the nature and microvariability of plutonium particles in the soil and unusual pathways of exposure, e.g., that which might be associated with cooking and washing outdoors and inadvertent soil ingestion. A study on the prevalence of thyroid disease is also being conducted and the geographic pattern of disease may be useful as a bioindicator of the geographic pattern of exposure to radioiodine. Finally, an examination is underway of gummed film, fixed-instrument, and aerial survey data accumulated during the 1950's by the Health and Safety Laboratory of the U.S. AEC. This article gives an overview of these many different activities and a summary of recent dose assessments. Health Phys. 71(4):438–456; 1996

Key words: dose assessment; exposure; radiation; fallout; ^{137}Cs

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INTRODUCTION

Bikini and Enewetak Atolls in the Republic of the Marshall Islands (RMI) were the sites of the U.S. atomic weapons testing program in the Pacific from 1946–1958. The Marshall Islands have been the subject of radiological investigation and dose assessment for several decades, yet prior to 1994, the nation in its entirety had never been systematically evaluated. In the past year, the RMI completed its own comprehensive evaluation of the radiological conditions of its islands (Simon and Graham 1994, 1995b) and addressed specific dose assessment issues as part of the Nationwide Radiological Study (NWRS, see Simon et al. 1993a for an overview). The study was administered by the RMI government and employed and consulted with scientists from the United States as well as other countries. The study was conducted independently of the U.S. Department of Energy (DOE), although the DOE still maintains environmental and health surveillance activities in limited areas of the nation as mandated under Public Law 99-239 (U.S Congress 1986). The independence of the NWRS was an important political issue within the RMI; satisfying the need for independence led to critical review, rather than simple acceptance, of previous radiological dose evaluations (Greenhouse et al. 1977; Bair et al. 1982; Lessard et al. 1985; Robision et al. 1982a, b; Robision and Phillips 1989). All previous evaluations of land contamination and possible radiation doses applied only to the more northern atolls; the NWRS was specifically designed to evaluate the entire nation.

A comprehensive radiological evaluation and assessment of potential doses for the entire nation had been needed for many years as evidenced by continuing queries of Marshallese concerning possible contamination of the many atolls and allegations of health effects. Dose assessment activities as a component of the NWRS fulfills a specific political role and public service, hence these activities are more than an academic exercise or a process of enlarging the database on health risks following radiation exposure.

Almost every adult citizen of the Marshall Islands knows of the atomic weapons testing program conducted four decades ago. Most citizens believe that a variety of ailments, thyroid diseases in particular, are a result of the U.S. testing program. Public understanding of radiation

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risk is critically needed in the RMI as it is in other nations with any radiological risks. Unnecessary fear about radiation can result in a detriment to societal well being as well as result in unnecessary fears of nuclear energy. In the RMI, the cross-cultural differences between scientists and the citizens of the RMI and the necessity of translating technical information to the indigenous language of the Marshall Islands represents especially difficult challenges.

The task of dose assessment in the RMI is inherently complex because of the number of different island locations. Although the Republic of the Marshall Islands is a small nation in terms of land area, it is composed of 29 atolls and 5 separate reef islands (see Fig. 1): the total number of islands exceeds 1,200. The exclusive economic zone of the Republic covers 2×10^6 km^2 although the total land mass is only 180 km^2. The combined land area of the islands within each atoll ranges from about 0.5 km^2 to 16.4 km^2. The lagoon areas also vary significantly, from 8.4 km^2 to over 2,500 km^2, the latter belonging to Kwajalein Atoll, the world's largest lagoon.

The nation's capital is located on Majuro Atoll in the southeast part of the nation, approximately 3,800 km west of Honolulu, HI, and 2,700 km north of Fiji. The atolls are arranged in two island chains running roughly NNW to SSE: the western Ralik ("sunset") Chain and the
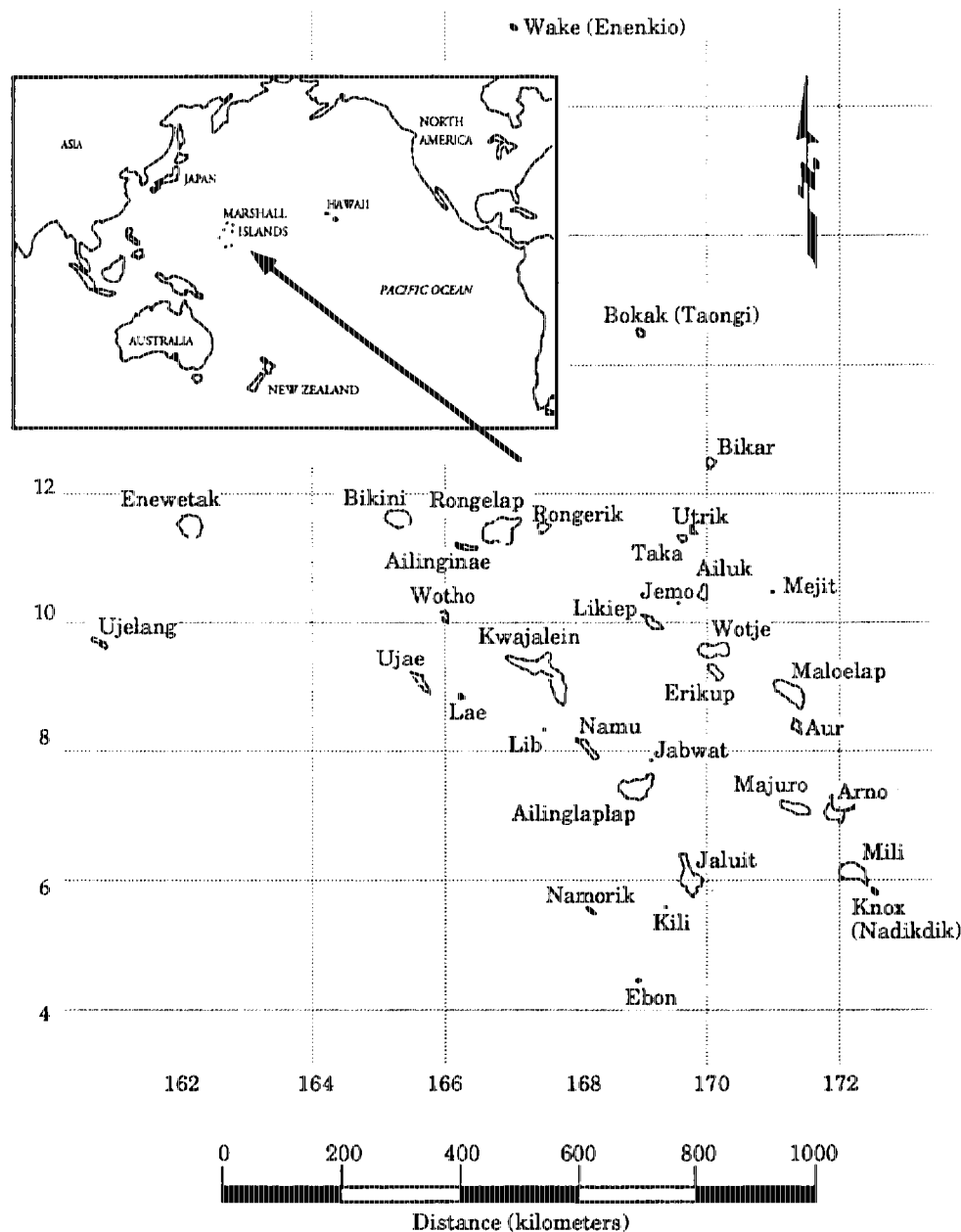

Fig. 1. Map of the Republic of the Marshall Islands.

eastern Ratak ("sunrise") Chain. The atolls are located within the latitude band extending from 4.5° to 14.5° N.

The total population today numbers close to 50,000 and is one of the fastest growing in the world today. As in any society, there are numerous public health issues in the RMI other than radiation: this is particularly the case in those countries like the RMI that have assimilated a western lifestyle and dietary habits within only a few generations.

Dose assessment activities currently underway emphasize recognizing important pathways of exposure, comparing and supplementing recent radiological data with historical data, and efforts at modeling traditional, contemporary and expected future lifestyles for various locations across the nation. In the viewpoint discussed here, dose assessment can pertain to past, present day, or future exposures.

It is the objective of this paper to cite numerous previous reports of radiological evaluations and dose assessments, to describe in detail some of the considerations for ongoing and future assessments, and to briefly present some recent dose assessment findings.

BACKGROUND

Needs for radiological assessment

The need for dose assessments in the Marshall Islands was suggested by Public Law 99-239 (U.S. Congress 1986, Section 177, Article VIII): "(a) The Northern Marshall Islands Radiological Survey[†] and related environmental studies conducted by the Government of the United States represent the best effort of that Government accurately to evaluate and describe radiological conditions in the Marshall Islands; and (b) the Northern Marshall Islands Radiological survey and related environmental studies have been made available to the Government of the Marshall Islands and can be used for the evaluation of the food chain and environment and estimating radiation-related health consequences of residing in the Northern Marshall Islands after 1978."

These statements make clear that the estimation of radiation-related health consequences, at least in the northern Marshall Islands, was of interest at the time P.L. 99-239 was written in the mid-1980's. The estimation of the number of expected radiation-related health consequence normally uses the collective radiation dose; dose assessment is, therefore, a necessary activity. However, P.L. 99-239 does not describe in any detail how past or present health conditions can be related to radiation exposure before 1978. Presumably, it was believed that all radiation related health effects had already been documented and that these conditions had occurred exclusively among the exposed Rongelap and Utrik

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[†] The Northern Marshall Islands Radiological Survey was an aerial survey and ground sampling radiological monitoring program of 11 atolls and 2 islands carried out in 1978 for the U.S. DOE by its contractors: Lawrence Livermore National Laboratory and EG&G Energy Measurements Group. Findings of the Northern Marshal Islands Radiological Survey can be found in EG&G (1981); Robison et al. (1981); Robison et al. (1982a); and Bair et al. (1982).
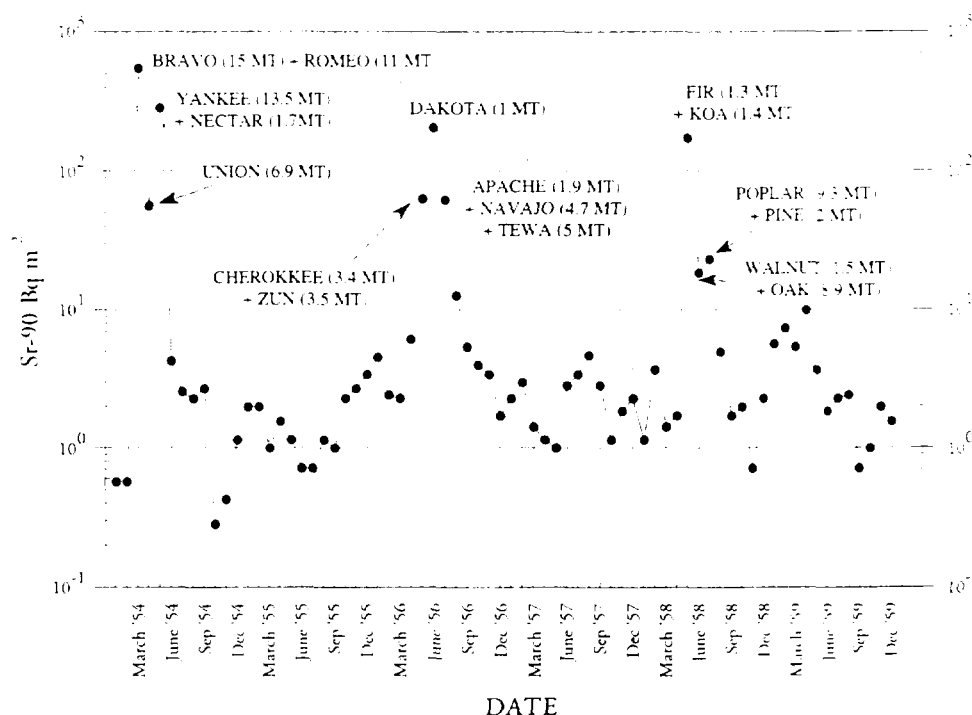
populations. (Note that the Bikini and Enewetak people had been moved away from their atolls while the tests were conducted.) Because radiogenic thyroid disease continues to be expressed for as long as 40 y or more after exposure (Shore 1992; Wong et al. 1993), these assumptions may not be valid.

The rationale for the design of the Northern Marshall Islands Survey was given in EG&G (1981): "The present survey covered those atolls known to have received direct fallout from the BRAVO event, conducted in March 1954 at Bikini Atoll... In addition, several atolls and islands which might have been at the fringes of the BRAVO fallout were also surveyed." Because of the absence of documentation to conclusively support which atolls had received fallout, the design of that study remained unconvincing to the Marshall Islands Government. An inspection of historical data validated the concern that the Northern Marshall Islands Survey did not utilize all possible information to determine those atolls that may have received fallout. For example, important data were collected by the Health and Safety Laboratory (HASL, now the U.S. DOE Environmental Measurements Laboratory) during the 1950's at Kwajalein Atoll. These data (Harley et al. 1960) are summarized here in a time-sequence plot of deposition during the years 1954 through 1958 (Fig. 2). As can be seen in Fig. 2, there were at least three periods when deposition occurred at Kwajalein Atoll at about 100× the background level. Kwajalein is a large atoll south of the region monitored in the Northern Marshall Islands Survey. The months in which the major weapons tests took place in the Marshall Islands are noted on the figure; the precise agreement of the data peaks and the test dates is revealing. Seventeen tests were conducted of a size of one-megaton explosive yield or larger, and the dates of all 17 coincided with the peaks of deposition at Kwajalein.

Kwajalein Atoll has been a site of a sizeable population for many years; the 1958 census of the Marshall Islands indicates that 9% (~1,300 people) of the Marshallese population lived there at that time. The need for dose assessment outside of the region covered by the Northern Marshall Islands Survey is apparent from reviewing the HASL data; this conclusion echoes the concern expressed by the population at locations across the entire Marshall Islands nation.

The historical evidence was of significant importance to the design of the NWRS monitoring and dose assessment program. The Northern Marshall Islands Survey had monitored only 30% of the land area of the nation. The implications of detectable radioactivity in Kwajalein immediately following the large tests provided some rationale for conducting a nationwide monitoring program and partly established the need for independent dose assessments.

Several other populated atolls are close by to Kwajalein Atoll (Fig. 1), and it is possible that they received at least an equal level of deposition. Whether significant amounts of short-lived radioiodines reached population

Fig. 2. Monthly gummed film monitoring results (^{90}Sr, Bq m^{-2}) at Kwajalein Atoll (daily data values from HASL-93 1960, summarized by author).

sites across the RMI depended on the direction of the fallout clouds and the time interval between the explosions and the arrival of the fallout. Although the amount of ^{137}Cs deposited at most of the atolls in the mid- and southern Marshall Islands is relatively low, calculations of fission yields indicate that the amount of ^{131}I produced is about 700 times the amount of ^{137}Cs. Moreover, local fallout deposition usually occurred within 48 h of the detonation (Breslin 1955); this short transit time implies that radioiodines would be part of the radionuclide mixture and could have led to exposure of residents' thyroid.

Assessment goals

The goals of the NWRS contemplated various types and uses of dose assessment (Simon et al. 1993a). In particular, the original objectives of the NWRS included "(1). . . to reassess the radiological conditions of Bikini, Enewetak, Rongelap and Utirik Atolls. . . performing dose computations (retrospective or prospective) in some cases and engaging in other relevant investigations to better understand any risk involved in inhabiting these atolls. (2) To provide advice to the RMI government and to the Nuclear Claims Tribunal [the organization responsible for dispensing compensation] for damages of effects likely associated with the derived radiation exposure levels and concerning health conditions which are related to radiation; also to assist in the determination of exposure and risk for individuals where appropriate or possible."

Compensation program

Radiological assessment in the Marshall Islands plays another very special role: that of providing data and, in some cases, evidence for an ongoing radiation exposure compensation program. The compensation program is administered by the Nuclear Claims Tribunal (NCT), a judicial body whose charge is to "render final determination upon: (a) claims past, present and future of the Government, the citizens and nations of the Republic for loss or damage to person or property which are based on, arises out of, or are in any way related to the Nuclear Testing Program. . . " (RMI 1987). The NCT became a reality following passage of the Marshall Islands Tribunal Act in late 1987.

In August 1991, certain medical conditions were used to establish "a list of medical conditions which are irrebuttably presumed to be the result of the Nuclear Testing Program." These conditions included solid tumors of most organs (e.g., breast, colon, liver, ovary, pancreas, stomach, bladder, thyroid) as well as leukemia, lymphoma, beta burns, and acute radiation sickness. For eligibility, the claimants must be Marshallese and have been present in the Marshall Islands at any time during the testing period of 1946–1958. For the conditions listed, a dose assessment is not needed. However, other categories of possible claims include damage to or loss of land and other medical conditions not covered by the presumptive list. To properly evaluate the likelihood that those conditions were radiogenic in origin, a credible dose assessment is of considerable importance.

Population description

One use of dose assessments is to estimate numbers of expected health consequences among a population. The usual dosimetric quantity of interest for such purposes is the collective dose equivalent S (ICRP 1977) or the collective effective dose (ICRP 1992). Regardless of the defined quantity that is used, the important task is to determine estimates of organ doses, which can be weighted with tissue weighting factors and radiation quality factors, over the distribution of population ages and sexes. A description of the population is fundamental to reconstruction of collective dose even though the number of observable health effects among a population is not reliably predictable.

The population size as a function of time and location is required to estimate the collective dose for predicting health consequences. In the case of the Marshall Islands, the population is distributed among many different locations. The population size in the Marshall Islands and the population distribution among atolls has changed dramatically since the period of nuclear testing with a pronounced migration to the established population centers in Kwajalein and Majuro. The change in size and location of the population is depicted in Fig. 3 (RMI 1990). Not represented in this figure are the two main Marshallese population centers on Kwajalein and Majuro Atolls. These two locations, representing the first and second most heavily populated centers, experienced annual growth rates of over 4% and 6%, respectively, during the 1980's. In absolute terms, the population size of Kwajalein and Majuro has changed from 1,284 and 3,415 to over 9,300 and near 20,000, respectively, during the interval from 1958 to 1988.

A few atolls have become reinhabited during the past three decades, while others have been abandoned. For example, Bikini was evacuated in 1946, and partially reinhabited in 1972; the population was again removed by the U.S. in 1978 when body burdens of ^{137}Cs increased 20-fold due to consumption of contaminated foods (McCraw 1979; Miltenberger et al. 1979). Today, most of the Bikini community lives on Kili Island in the south part of the nation though part of the community resides on Ejit Island in Majuro Atoll. Rongelap was evacuated about 50 h after the BRAVO test in 1954 and reinhabited in 1957; the people of that community then abandoned their home atoll (as well as Ailinginae and Rongerik) in 1985, as a result of fear engendered in the community following the release of a DOE report (U.S. DOE 1982) in 1982. This report indicated for the first time that contamination levels on part of Rongelap Atoll were equivalent to those on Bikini Island. In 1971, a limited number of people reinhabited Enewetak only to leave in 1977 due to poor food supply. Since then, the Enewetak people have sporadically moved between Ujelang and Enewetak. The nomadic existence of those who were displaced, directly or indirectly, by events related to the nuclear testing program, is not their preferred lifestyle. The loss of homeland for these people, either for reasons of true safety or due to their fear, has resulted in a diminished sense of community and loss of cultural continuity.

Most of the locations at which the people of Enewetak, Bikini, and Rongelap lived did not provide any substantial exposure and, thus, generally reduced the overall risk to the community as compared to their home atoll. However, for the purpose of estimating collective
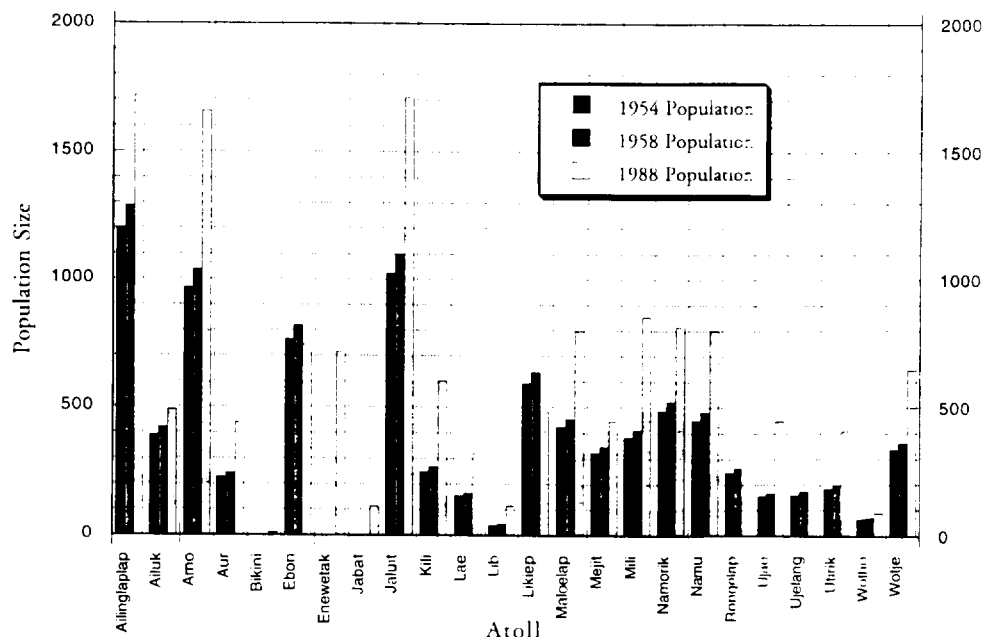

Fig. 3. Population sizes for the atolls of the Marshall Islands in 1954, 1958, and 1988. The main population centers of Majuro (Majuro Atoll) and Ebeye (Kwajalein Atoll) are not shown (see text for more information).

exposure, the task is made considerably more complex by the number of other locations to which individuals may have moved.

Time and size distribution of tests

Prior to December 1993, the yields of 45 of 66 tests conducted in the RMI were still classified data. The Marshall Islands Government requested these data in 1992, and, in late 1993, U.S. Secretary of Energy Hazel O'Leary, through an "Openness Initiative," announced the yields of the remaining 45 tests (U.S. DOE 1993a, b).

Table 1 shows the annual total explosive yield during the years of atomic testing in the Marshall Islands. The explosive yield of the largest test in the Marshall Islands was 15 MT equivalent TNT. Seventeen tests in the RMI were of a yield greater than 1 MT each: these tests contributed about 95% of the total yield. The early years of the testing program, 1946 through 1951, were relatively inactive in terms of proportion of the total yield (1.07 × 10^8 tons TNT).

Information concerning the island locations of the tests, on-site meteorology, deposition patterns, etc., are contained in DNA (1979), an extraction of information from the classified DASA 1251 series of reports (Morgenthau et al. n.d.). Some of the history of the testing era can be found in different forms in Hines (1962), Deines et al. (1991), and Schultz and Schultz (1994).

Global fallout

It is widely known that there are varying levels of fallout radioactivity at locations worldwide as a result of weapons tests conducted by the U.S. and other nations. Northern hemispheric locations near the equator are known to have a minimum deposition of fallout radioactivity (Machta et al. 1956; Eisenbud 1987) while locations at mid-latitudes received greater amounts. Global fallout has been deposited within each hemisphere somewhat differently, but it is usually correlated with local rainfall rates as well as latitude.

Substantial variation of global fallout over the area of the Marshall Islands might be expected because of the wide range of latitude over which the islands are located and as a result of strong rainfall gradient across the

Table 1. Distribution of test yields among years and between Bikini and Enewetak test sites

Year	Percent of total yield*
1946	0.04%
1948	0.1%
1951	0.3%
1952	10.2%
1954	45.0%
1956	19.4%
1958	24.9%
Bikini	71.8%
Enewetak	28.2%

* Total yield equalled 1.07 × 10^8 tons TNT; Bikini and Enewetak test sites combined.

nation. Southern atoll locations receive approximately 300 to 430 cm of rainfall annually: northern atolls receive considerably less, on the order of 100–175 cm annually (NOAA 1989a, b). Estimates of global fallout ^{137}Cs for each atoll have been made by McEwan[1] and Simon[2] using a predictive model based on latitude and annual rainfall rates, the model having been calibrated with published deposition data (HASL 1977; Larsen 1985) from a variety of locations in the mid-Pacific region that are outside the RMI. Although deposition generally increases with increasing latitude in the northern hemisphere, annual rainfall rates across the archipelago vary in the opposite direction, thus negatively compensating for the a latitudonal increase. Predicted values of global fallout deposition are close to uniform across the Marshall Islands. Predicted deposition values of ^{137}Cs from global fallout vary between 400 and 800 Bq m^{-2} for the atolls of the Marshall Islands.

While global fallout does not substantially contribute to the dose commitment for individuals, it does contribute to the collective dose. More importantly, estimating the expected level of global fallout at each atoll assists in determining which atolls did not likely receive locally produced fallout. The estimate of global fallout is also used to determine the fraction of the total fallout radioactivity measured at each location that can be attributed to the weapons testing program in the RMI.

EXPOSURE PATHWAYS AND RELATED DOSIMETRIC CONSIDERATIONS

The recognition of relevant exposure pathways is vitally important for producing credible dose assessments. Assessments for inhabitants of the Marshall Islands are unique compared to U.S. scenarios for several reasons. First, there are dietary components and minor pathways that are normally not of concern. Second, the relative importance of different exposure pathways has substantially changed during the decades since the nuclear tests were conducted. Various issues of exposure pathways and dosimetric considerations are discussed here.

Diet

One of the most dramatic alterations within the Marshallese culture over the past four decades has been acceptance of dietary changes, including the introduction of prepared and packaged food items. The degree of acceptance of these changes and the availability of westernized goods varies among atoll communities within the Marshall Islands. Some communities remain today more isolated from such changes because of their remoteness from frequent shipping traffic or because of their low level of economic development that precludes them from purchasing expensive prepared foods.

[1] McEwan, A.C. Caesium-137 Deposition from global fallout in the Marshall Islands. 1992.

[2] Simon, S.L. Comparison of recent ^{137}Cs measurements with prediction of a global-fallout deposition model and historical data. 1993.

Those communities directly affected by the nuclear testing program have received various types of compensation over the years that has resulted in dramatic changes to diet. For example, the communities of Enewetak (sometimes resident on Ujelang Atoll), Bikini (now resident on Kili Island and Ejit Island. Majuro Atoll), Rongelap (now resident on Mejatto Island and Ebeye Island. Kwajalein Atoll and Majuro Atoll), and Utirik, receive U.S.D.A. surplus foods that are almost entirely canned except for packaged rice. The distribution of these foods began before the Compact of Free Association (U.S. Congress 1986) was signed into law in 1986 and will continue at least through fiscal year 1996. The food program, intended to only provide supplementary sustenance, provides food to 2,875 persons with a total annual expenditure of about $0.5 million. These communities also receive quarterly compensation payments since the initiation of the Compact. Thus, the two communities having received the greatest individual exposures, i.e., Rongelap and Utirik, and the two communities whose land was most heavily contaminated, i.e., Bikini and Enewetak, have experienced significant change from traditional dietary patterns. Attempts at retrospective assessments for the years following the BRAVO incident, therefore, must take account of these changes over time.

The lifestyles of the people of Enewetak, Bikini, and Rongelap have not yet stabilized because of uncertainties about the location of their future home life. Their lifestyles, therefore, will continue to change in concert with decisions they make concerning rehabitation of their traditional homelands. Present day and prospective assessments for these communities, therefore, must rely either on assumptions concerning expected future dietary practices, or they must use a traditional dietary description to determine dose commitments for those people who might choose, or who find it necessary, to return to traditional diets. Experiences in developing nations sometimes indicate that the younger population tends not to revert to traditional dietary patterns if newly introduced foods are maintained in sufficient supply through more than a single generation. Thus, the determination of present and future exposure based on traditional dietary patterns is argued by some not to be of importance today. However, critics of prospective dose assessments that are based on a traditional diet may not have considered that the availability of compensation money and food supplementation programs may end within the immediate future. Thus, these communities may be forced for economic reasons to revert to more traditional means of sustenance. Thus, dose assessment based on a traditional diet may have continued relevance for certain segments of the Marshall Islands population, in particular for those most directly affected by the atomic testing program.

The degree to which local food is used in the diet is to some degree a function of location; imported food shipments arrive more regularly and in greater quantity to communities that produce more *copra* (dried mature coconut meat) for resale and which are more accessible due to safe reef conditions. Seasonal variations in diet are also a part of the yearly cycle as many adult Marshallese prefer breadfruit and other local fruits when available. Variations in diet can also be linked to meteorological events, in particular those of disaster proportions, e.g., typhoons. Following typhoons, communities may depend entirely on what little local food is available because of delays in the arrival of disaster relief. Similarly, once disaster aid reaches communities and the small amounts of locally grown food are depleted, the diet may consist entirely of imported food for many months. During these periods, Marshallese at other atolls frequently send locally produced fruit or fish to their extended families as part of a relief effort. These various types of events add considerably to the difficulty in modeling long term food sources either for the purpose of individual or collective dose assessments.

Food plants

A small variety of plants are used traditionally in the Marshall Islands for sources of food. In particular, the coconut palm (*Cocos nucifera* L.) is a versatile tree bearing nuts that are consumed in numerous different forms. Commonly drunk for body fluid replenishment, the young "drinking coconut" or *ni* (ne), provides a clear slightly sweet liquid. Inside the drinking coconut is a soft, gelatinous layer called *mede* (me' dā), normally scooped out with one's fingernail and eaten. Other stages and forms of the coconut used for food are the coconut cream—the thick milk obtained from the fully mature coconut called *dren in waini*; hard coconut meat or *waini* (why' ne)—the thick coconut meat from the mature coconut, usually made into shavings and combined with rice or other foods; the coconut embryo or *iu* (yū)—a sweet spongy material obtained from the center of a sprouted coconut; *jekero* (jek' a roo)—the liquid sap of the coconut tree collected from the severed end of a coconut palm branch; *jekmai* (jek' ma yī)—a thickened version of *jekero* produced by boiling, used as syrup; and *jekmanin* (jem' a ung)—an alcoholic drink made by fermenting the *jekero*. The coconut husk is sometimes sucked to gain access to the interfibrous water; *kenawe* (ken' a we) has been reported to be mostly commonly consumed by women in the early stages of pregnancy.

Concentrations of cesium tend to increase with the age of the coconut and the density of the food product, with *waini* having a considerably higher concentration than *ni*. Coconuts are common in virtually every location of the Marshall Islands; over 60% of the land area is covered by forests of coconut palms (RMI 1991).

Other locally grown fruits that are not cultivated but normally picked wild are Pandanus (*Pandanus fischerianus*. Marshallese: *bob*), papaya (*Carica papaya* L. F., Marshallese: *keinabbu*), breadfruit (*Artocarpus incisus*, Marshallese: *ma*), including the preserved product *bwiro* (breadfruit mixed with arrowroot and *jekero*, wrapped in breadfruit leaves and baked). In some locations, limes

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grow wild as well as a small variety of bananas (pinana), the latter normally requiring planting and a minimal amount of care. In some communities, common varieties of watermelon and pumpkins are grown in gardens. Except for the production of taro, a marsh plant used for a variety of food preparations and medicine, organized agriculture is not commonly practiced in the Marshall Islands.

Used more in decades past, the Polynesian Arrowroot (Tacca leontopetaloides) or makmōk (mak' mek), was commonly tended to produce tubers, then harvested, leached in a lengthy process to remove bitterness and finally formed into a starchy material that provided the basic carbohydrate dietary component. Makmōk was a versatile food product and could be kept for long periods of time. A common notion across the RMI today is that arrowroot does not grow well or in some cases has ceased to exist as a result of atomic bomb radiation. Observations on the propagation of this belief were discussed by Spenneman (1992); he concluded that the decrease in availability of arrowroot is a by-product—not of radiation exposure but of the diminishing need to use, and thus to cultivate, the food crop. Commercial availability of flour and rice have contributed to the decline in the cultivation and usage of arrowroot.

The potential for uptake of ^{137}Cs is similar in most fruiting plants though differences in uptake are apparent. In particular, the Pandanus accumulates cesium to a higher degree than other fruiting plants though root crops can also accumulate significant cesium. Recent measurements of ^{137}Cs from Rongelap Island gave average values of 200 Bq kg^{-1} for mede, 20 Bq kg^{-1} for ni, 900 Bq kg^{-1} for makmōk (dry weight), 1,000 Bq kg^{-1} for bob (dry weight), and 470 Bq kg^{-1} for ma (dry weight) (Simon and Graham 1995a).

Seafood

Fish are an important part of the traditional Marshall Islands diet (see for example Chakravarti and Held 1963; Naidu et al. 1981). Questions are commonly asked in the Marshall Islands about the possible contamination of fish, both in the present and in the past tense. Providing a true comprehensive answer to this question is difficult as from 250 species (Myers 1989) to over 800 fish species (Randell and Randell 1978) have been documented in the waters of the Marshall Islands.

Possibly the first scare over radioactive contamination of fish took place following the BRAVO test in 1954. Eisenbud (1990) describes a "Tuna Panic" in Japan, and, although he notes it to have been unwarranted, he acknowledged the difficulty in monitoring hundreds of tons of individual fish for contamination as well as the problem of determining a contamination standard for acceptance or rejection of fish.

The idea that pelagic fish are freely moving brings to mind two important, but different, possibilities. First, the opportunities for pelagic fish to inhabit a variety of oceanic locations, including those having received low levels of fallout, would tend to reduce the likelihood of

high concentrations in fish flesh from occurring. This same phenomenon, however, raises local concern because there remains a finite possibility of fish bringing contamination from areas near the test sites to more distant locations. A related concern is that many types of locally produced food, including fish, have been shipped for decades by families to remote family members on other islands. This ad hoc food distribution network is nearly impossible to model because of the lack of documentation. Even so, the possibility of sending contaminated fish from one location to another remains a small but finite possibility.

For retrospective assessments, several nuclides may be important. For example, the concentration of ^{55}Fe (t$_{1/2}$ = 2.7 y) was determined in people and fish from Rongelap Atoll (Beasley et al. 1972). ^{55}Fe was one of three radionuclides present in significant quantities (along with ^{137}Cs and ^{90}Sr) 3 y after exposure in 1957. Measurements of ^{55}Fe concentrations in liver of goatfish sampled from Rongelap Atoll over the years 1959 through 1963 showed steadily decreasing concentrations with a representative value of 2×10^5 Bq kg^{-1} (wet weight).

In the area of the northern Marshall Islands, representative concentrations of ^{137}Cs in reef fish are 0.6 Bq kg^{-1} wet weight (decay corrected from 1982 data) (Robison 1982a; Noshkin et al. 1981b). Fortunately, both reef and pelagic fish generally provide a relatively uncontaminated source of food today, regardless of location.

Plutonium concentrations were reported in fish from Kwajalein Atoll (Noshkin et al. 1979) to determine whether fish collected there were substantially higher in activity than as expected from global fallout as had been earlier reported (U.S. DOE 1973). Noshkin et al. (1979) concluded that concentrations of ^{239,240}Pu in the flesh of fish from Kwajalein were of the order 1×10^{-4} Bq kg^{-1} (wet weight) as was expected based on global fallout alone.

Food collection

Food is often collected by community members from a number of islands other than where the community resides. In some cases, Marshallese will visit other atolls for the purpose of collecting food, e.g., Taka is used as a "pantry" for food resources for the people of Utirik (Thomas et al. 1989) even though it received approximately equal deposition as Utrik. There is also significant concern about radioactive contamination of certain foods (e.g., coconuts and coconut crabs) at Rongerik Atoll (Thomas et al. 1989), a pantry atoll owned by the people of Rongelap. Rongerik Atoll received approximately equal deposition as Rongelap Island (Simon and Graham 1994). Realistic radiological assessments must determine locations from which foods are derived, the quantities and types of foods involved, and the location of specific radionuclide concentrations.

Medicinal plants

A variety of plants are used traditionally for medicinal purposes in the Marshallese culture. but the species. preparation methods. and dosages are not well documented. Whistler (1992) has reported extensively on the variety. uses. and preparation methods of medicinal plants on other islands in Polynesia and although some of the same plants used there are the same as in the RMI. there is a paucity of written information about their use in Marshall Islands culture. A systematic study of ^{137}Cs concentrations in five species over the geographic range of the Marshall Islands was conducted by Duffy (1994) as part of the NWRS activities. Sampling and radiological analysis of these native vegetation species used in traditional Marshallese medicine was carried out to complement the assessment of potential exposure via ingestion of foods. The uptake potential of these plants across the environment of the RMI has not been studied in the past and. although the ingestion of these plants likely makes up a small part of the plant material and radioactivity consumed by Marshallese. the dose contribution of this pathway was previously unexplored.

Species and plant parts included in the study by Duffy were the fruit and leaves of *Morinda citrifolia* and the leaves of *Tournefortia argentea. Scaevola taccada. Triumfetta procumbens*. and *Polypodium scolopendra*. Plant concentrations generally decreased from north to south, with values of 1.400 Bq kg^{-1} (dry weight) representative of the northern atolls. decreasing to 1 Bq kg^{-1} at the southern atolls. Some difference in uptake between species was noted: however, for dose assessments, the most important factor is the recognition of the pathway and obtaining some credible estimates of intake rates. Duffy determined the dose commitment per medicinal administration after making some assumptions regarding the amount of plant used in the preparation. The frequency of usage. however. is still quite uncertain and likely varies between the more urbanized population centers and the more traditional communities of the remote atolls.

Water

Potable water remains today a valuable commodity in the Marshall Islands as both standing or running fresh-water are virtually non-existent: only one lake exists on Mejit Island and it varies from fresh to brackish. Running fresh-water exists only episodically during heavy rain storms: even then. permeation into the soil is rapid. Some below ground fresh water does exist on the larger islets in the form of shallow Ghyben-Herzberg lenses floating on denser sea-water in the porous soils (Thomas et al. 1989). although such ground water is not uniformly present or accessible. On remote islands, groundwater is normally used for drinking only in times of drought. although it is often used for dish washing and bathing.

Nearly all water used for human consumption in the Marshall Islands is collected rainwater. In the capital city of Majuro. for example, the airport runway functions as a large rainwater catchment system: this system collected approximately 200 million gallons in 1989 (RMI 1990). Most families. particularly those outside of Majuro. collect rainwater in a concrete or fiberglass cistern via home roof collection and gutter drainage systems. Few open cisterns exist today: however. many were apparently used in past decades.

Retrospective dose assessments must consider the possibilities of drinking water containing radioactive contamination as a result of rainout from direct (dry) fallout deposition into open catchments or from water collection on contaminated roofs that fed into catchments. The contribution of radioiodine in drinking water to the exposure of the Rongelapese following BRAVO was considered by Lessard et al. (1985). Only 23 cm of water were reported in each of eight catchments on Rongelap Island during the days following BRAVO (Sharp and Chapman 1957). The low water levels did not tend to concentrate activity according to Lessard et al. (1985): they assumed 20% solubility of iodine from the fallout particles and 50% to 80% of the particles to have settled out of the liquid phase.

Questions are sometimes raised about the possible contamination of cistern water collected from roofs that may have been contaminated from resuspended dust. Although the soil/roof/water catchment pathway could only contribute a very small increment of exposure compared to that from locally grown fruits. further reviews of such possibilities are still needed for a truly comprehensive evaluation.

Present day assessments generally do not need to consider contamination of ground water because of the low concentrations. The concentrations of radioactivity were reported by Robison et al. (1982a) for northern Marshall Islands locations (also see Noshkin et al. 1981a): current values for ^{137}Cs in well-water on Rongelap Island. for example, are on the order of 0.1 Bq kg^{-1} (decay corrected from 1982). Concentrations for ^{239,240}Pu are approximately a factor of 100 lower.

Soil characteristics related to plant uptake

Soil on the islands within the Republic originated from the detritus of corals and other marine life. and was later stabilized by plants (Gessell and Walker 1992) and slowly improved in quality by the buildup of organic detritus. Details of soil development have been described by Fosberg and Carroll (1965) and mineralogical and descriptive classifications have been discussed by Morrison (1990). Mineral content is significantly lower in coral based soil than that of continental soils. the atoll soil being nearly completely dominated by calcium carbonate with magnesium carbonate as a secondary component. The low occurrence of minerals. potassium in particular, leads to relatively high levels of uptake of radioactive ^{137}Cs. The implications of a low potassium environment are important for creating the potential for high exposures to humans to occur wherever substantial amounts of ^{137}Cs were deposited.

The opportunity for mitigation of cesium uptake in plants exists. however. with the application of potassium

rich fertilizers. Robison and Stone (1992) reported on the substantial effect of suppressing ^{137}Cs uptake by the addition of potash fertilizer. Use of mitigation procedures, e.g., potassium fertilizer, and their effectiveness must be considered in future assessments.

Soil ingestion

One pathway of particular concern in locations with ^{137}Cs values exceeding a few thousand Bq m^{-2} of Cs or 1,000 Bq m^{-2} of ^{239,240}Pu is the potential risk to children as a result of intentional or accidental ingestion of dust or soil particles containing plutonium. In youngsters, mouthing behavior and deliberately eating soil is a well-documented worldwide phenomenon (see for example, Halsted 1968). Soil in the Marshall Islands appears not to be as palatable as at other worldwide locations because it does not contain clay, usually the component sought by children or adults who engage in geophagia (soil pica). Accidental soil intake is not bounded by soil type, thus this pathway deserves consideration.

Inhalation

The evaluation of inhalation dose can be a particularly complex issue because of the numerous types of exposure conditions and environmental variations that can be encountered and because data required to model these situations are normally difficult to obtain.

Partial guidance as to the relative importance of inhalation can be found by examining the dose conversion factors (Sv Bq^{-1} inhaled or ingested) for important radionuclides and the likely amount of radioactivity intake (Bq d^{-1}) possible via inhalation as compared to ingestion. For ^{137}Cs and ^{131}I, the ingestion and inhalation dose conversion factors are nearly equal (Eckerman et al. 1988), thus differences in intake between the pathways result mainly from the differences in density of air and foods and the total volume inhaled compared to the mass intake of foods. For ^{239}Pu, the inhalation dose conversion factor is several hundred times greater than for ingestion.

In a retrospective evaluation of thyroid exposure to the inhabitants of Rongelap in 1954, Lessard et al. (1985) concluded that inhalation could not account for the estimated intake of ^{131}I and that if it were assumed to, lethal exposures of external radiation would have been sustained. Neither was resuspension deemed as a reasonable alternative to ingestion.

An evaluation of present day inhalation dose by Robison et al. (1982b) indicates that although inhalation is a major source of exposure to transuranic radionuclides, both the inhalation pathway and the transuranics will contribute only a minor portion of the total dose predicted over the next several decades. In evaluating current and future inhalation dose commitments, it is necessary to know both the respirable fraction of the soil as well as the specific activity associated with that fraction. Robison et al. (1982b) reported respirable fractions of 19–24% at Bikini Atoll. Although those data do not specify the specific activity as a function of the respirable size fraction, an enhancement factor (EF,

$^{239+240}$Pu in the collected aerosol mass divided by surface soil concentration) provides nearly the same information. As expected, certain environmental conditions, e.g., bare fields and tilling operations, increase the EF.

Other types of studies have produced data that may be useful for inhalation calculations. For example, Simon et al. (1995) reported on findings of investigations to determine the spatial uniformity and size of transuranic particulates in the soil from Rongelap Island. Using track detector technology, verified by radiochemistry/alpha spectrometry, the particle size fraction less than 40 μm tends to have the highest transuranic specific activity. These data also show that in 5–10% of microvolumes sampled (approximately 20 μg each), a large fraction (30–70%) of the alpha emissions originate from a hot particle.

Previously NCRP (1975) concluded that particulate plutonium in the lung is no greater hazard than the same amount of plutonium more uniformly distributed throughout the lung. However, there is not yet clear evidence of how the absolute amount of plutonium that might be inhaled varies with the presence of hot particles in the soil. This situation is further complicated by the size distribution of soil particles to which the radioactivity may be attached.

Although most evidence indicates that inhalation of transuranics in the Marshall Islands is a small contributor to total dose, some cultural specifics should be considered. In particular, the open air design of houses in the Marshall Islands generally promotes resuspended soil material to enter homes as well as the accumulation of dust with much the same radioactivity concentrations as found out-of-doors. Most Marshallese houses, particularly those on less urbanized islands, typically do not have furniture; inhabitants sit and sleep on the floor. Moreover, windows are placed at ground level so as to promote ventilation while sleeping on the floor.

Other pathways

Other lifestyle attributes of Marshallese will likely affect the relative importance of minor pathways. In particular, the closely related activities of food preparation, cooking, washing dishes and storing dishes out-of-doors all provide possible means of transporting radioactive contamination to humans. Food preparation may take on many forms including catching fish, drying fish in the sun (normally on the roof of a house), cooking over an open fire, baking in a fire pit, boiling water in open pots, etc. Food is often consumed outdoors, particularly in the less urbanized islands. In the past, such practices would have been common nationwide. Dishes are also washed outdoors, typically not far from the site of the fire pit or kerosene stove. Dishes are usually dried outdoors and sometimes stored there.

For the purpose of long-term assessments, the dietary behaviors of animals that are eaten should be considered. Pigs and chickens are commonly left loose on many islands to forage for food in the undeveloped

parts of the island; food for pigs includes coconuts fallen from trees, plant roots, insects in the soil, and scraps from human meals. Pigs, in particular, can ingest relatively large amounts of soil while foraging. Thus, the transport of soil radioactivity to humans via consumption of pig flesh and edible organs requires consideration. Pig flesh from Rongelap Island was recently analyzed for ^{137}Cs concentration as part of a study of the safety of Rongelap for future residents. Representative values of pig flesh were 400 Bq kg^{-1} (dry weight) [137]Cs.

The coconut crab (*Birgus latro*) was recognized as accumulating significant amounts of ^{137}Cs from studies on Rongelap following the BRAVO fallout incident. Chakravarti and Held (1960) reported concentrations in 1958 of 500 disintegrations min^{-1} g^{-1}—that is equivalent to nearly 1×10^4 Bq kg^{-1} (dry weight). This value is only slightly higher, after accounting for radioactive decay, than recent measurements that are of the order of 350 to 1,000 Bq kg^{-1}. The diet of the coconut crab is mainly coconut meat; thus, the crab flesh can be in equilibrium with, or somewhat greater than, the concentration of ^{137}Cs in coconut meat. The coconut crab is a unique food that must be considered in assessments; the crab is considered a delicacy by Marshall Islanders and is often eaten in large numbers when available. A recent report in the RMI (Crawford 1992), however, lists the coconut crab as endangered because they are relatively easy to catch and are very slow growing.

Lessard et al. (1985) discussed living conditions in the context of determining thyroid dose to Rongelapese exposed to BRAVO fallout. They concluded that ingestion was by far the most important route of intake for the Rongelapese exposed to BRAVO fallout and that this route included contamination from hands, plates, and eating utensils.

DOSE ASSESSMENT METHODOLOGY AND DATA

Historical radiological data

Comprehensive radiological data were collected and reported by HASL from the 1952 Operation IVY (Breslin and Cassidy 1955) and the 1954 Operation CASTLE (Eisenbud 1953). Operations IVY and CASTLE provided 10% and 45%, respectively, of the total explosive yield of the testing program conducted in the RMI. Three types of monitoring data were collected by HASL: (1) fixed-instrument exposure-rate measurements using stationary meters placed at numerous atolls, (2) measurements from aerial surveys immediately following many tests using a scintillometer that could measure over the range of 7.2×10^{-7} to 7.2×10^{-2} C kg^{-1} s^{-1}, and (3) measurements from gummed film placed at a Kwajalein Atoll, a central atoll location in the archipelago. The gummed film station, one of more than 100 monitors placed worldwide, collected fallout for 24 h, after which the film was changed and sent to HASL for analysis. The fixed-instruments provided exposure-rate data in the form of strip chart recordings. The output from those

instruments has possibly the greatest value for retrospective dose assessment because they indicate unequivocally whether local fallout arrived at the atoll, the time of arrival of the fallout, and the decay-rate. The elapsed time from detonation to deposition and the duration of fallout are important parameters for determining the possible exposure to the rapidly changing radionuclide mixture.

Other types of relevant historical data were reported by Sharp and Chapman (1957) who recorded a detailed description of the Rongelap community, the status of their food and water supplies, and events that took place following the BRAVO test. Sharp and Chapman also included in their report the evacuation and decontamination procedures and the film badge readings and exposure-rate readings from the bodies of Marshallese and U.S. weatherman stationed on close-by Rongerik Atoll.

Information on fallout transit time to Rongelap an Rongerik can also be deduced from Sharp and Chapman (1957); they reported the onset of visible fallout at approximately 1,400–1,430 h (the test was conducted at 0645 local time, DNA 1979) and that the ATN/3a Recording Dosimeter at Rongerik went off scale (at 7.2×10^{-3} C kg^{-1} s^{-1}) at approximately H + 6 h and 48 min (i.e., 1,333 h). It is difficult to determine if these observations are entirely consistent. Uncertainty in times of fallout arrival are important because of the rapid rate of change of radionuclide mixture soon after the detonation. Some level of interpretation is often required when using historical data. Similarly, the duration of fallout at Rongelap has required considerable interpretation; that uncertainty was described by Lessard et al. (1985).

Contemporary radiological data

The essential ingredient to dose assessments, retrospective or prospective, is a comprehensive database of location-specific radiological measurements and specific activities in soil and foods. Several surveys of Bikini and Enewetak have been conducted over the past several decades as part of U.S. sponsored cleanup or evaluation programs; however, in 1978, the U.S. Department of Energy sponsored an aerial gamma spectrometry survey of the atolls of the Northern Marshall Islands (EG&G 1981) supplemented with limited ground sampling. Verification of those data and collection of new radiological information on the rest of the atolls of the RMI was the primary task of the NWRS. In that study, extensive *in-situ* gamma spectrometric measurements (91 m height) were conducted for the purpose of determining soil areal inventories of gamma emitting radionuclides, e.g., ^{137}Cs, [241]Am, and [60]Co. All 29 atolls and 5 reef islands of the Marshall Islands were monitored at an average *in-situ* sampling density of 10 gamma measurements per km^2.

In the Nationwide Radiological Study, external exposure-rate estimates and calculations of areal inventory (Bq m^{-2}) used established *in-situ* spectrometry methodology (see Beck et al. 1972; Beck 1980; Helfer

and Miller 1988). The conversion of external exposure to dose used data from Jacob and Paretzke (1986) and ICRP (1987). The environmental measurements were supplemented by laboratory gamma spectrometry measurements of 30-cm-deep soil profiles (increments of 5 cm each) and surface soil samples (0–5 cm) analyzed for transuranic radioactivity.

Environmental count-rates and soil inventories in the nationwide study varied over four orders of magnitude; the lowest values ($<$ 500 Bq m^{-2} 137Cs) were measured in the southern Marshall Islands, and the highest values ($>$ 5 $\times$ 10^5 Bq m^{-2} 137Cs) were at Bikini, Enewetak, and Rongelap Atolls. These various data have recently been made available (Simon and Graham 1994, 1995b).

Considerations of spatial variations

Extensive monitoring of Rongelap Island was conducted in 1992 and 1993 (Simon and Graham 1995a) for determining compliance with a dose action level (RMI/RALGOV/DOE/DOI 1992). The demands of that study highlighted the need for techniques that could contribute to interpretation and extrapolation of data. In particular, geostatistical variogram modeling (see for example Cressie 1991) was used to deduce the spatial dependence of the *in-situ* gamma spectrometric measurement data and to predict values (kriging) at locations intermediate in location to those sampled. Attempts at applying conventional geostatistical analysis techniques to the Rongelap monitoring data have pointed out needs for innovation—in particular, the need for non-Gaussian distributional assumptions (Diggle et al. 1995). Though not a panacea for insufficient data, geostatistical modeling may improve the reliability of environmental contamination estimates that are made by simple linear interpolation or other algebraic weighting procedures. Use of geostatistical analysis to increase the spatial resolution of the local radionuclide inventory particularly improves the capability of calculating spatially averaged exposure-rates.

Spatial variations in the radionuclide inventory in different sections of Rongelap Island have been documented (EG&G 1981; Simon and Graham 1995a). A variety of assumptions, therefore, were recently considered for the size of the portion of island that residents might frequently use for the purposes of collecting food (SMT 1995). Environmental radioactivity and exposure-rates were spatially averaged for the purpose of simulating the exposure that island residents might acquire during food collection activities on various sized parcels of land (e.g., 200, 500, and 1,000 m). These "radii of utilization" were judged to be relevant to the lifestyle of past or future Rongelap Island residents since nearly all food collecting is conducted by walking. The effect of increasing the radii of utilization is to narrow the distribution of exposure-rate values around the mean value and to reduce the dispersion of predicted doses.

Dietary data

The use of contemporary radiological measurements in prospective assessment is generally a straightforward task; the main difficulty is determining relevant dietary descriptions for future inhabitants. Most previous assessments for inhabitants of the Marshall Islands have used dietary descriptions published by Naidu et al. (1981) or unpublished dietary information provided by the Micronesian Legal Services Corporation (see Robison et al. 1982a, b). A comprehensive analysis of the chemical composition of the Rongelapese diet was reported by Chakravarti and Held (1963) although most models apparently have not used those data. Recently, Dignan et al. (1994) reported a summary of a dietary survey of the Rongelap community, resident since 1985 in Kwajalein Atoll. The objective of that study was to determine the distribution of caloric intakes, primarily among the adult population, and to translate those data into a set of alternative diets of local foods. These dietary descriptions were subsequently approved by the Rongelap community to represent their average eating habits currently and as they would live on Rongelap under more traditional living conditions. These results provide a unique solution to determination of traditional diet, one of the main problems of dose reconstructions to island inhabitants. Notwithstanding that there is great uncertainty in applying the dietary results to any single individual, the data can be used to describe both the current diet, which is mainly composed of imported foods, and various options for more traditional eating habits. It is expected that this dietary description can be reviewed by other communities in the Marshall Islands so that amendments relevant to individual communities can be made, if necessary.

Deposition of individual radionuclides

A method of calculating concentrations of individual radionuclides on the ground following fallout deposition was published by Hicks (1982). The use of Hicks (1981) NTS data made possible dose reconstructions in Nevada (Anspaugh and Church 1986; Anspaugh et al. 1990; Beck and Anspaugh 1990) and in Utah (Simon et al. 1990; Stevens et al. 1990; Stevens et al. 1992). Calculational results of relative external gamma radiation exposure-rates and related radionuclide ground deposition specifically for Pacific tests was published by Hicks (1984) for the events MIKE (Operation IVY); BRAVO, ROMEO, and YANKEE (Operation CASTLE); and ZUNI, TEWA (Operation REDWING).

Measurements of external exposure-rate (e.g., from Eisenbud 1953) can be used, for example, to determine the local concentration of the radioiodines. The reported exposure-rate needs to be first corrected to 12 h post detonation using the exposure-rate decay data of Hicks (1984); the concentration of each radioiodine can then be determined at the time of fallout arrival (or any other reference time) using Hicks' normalized deposition factors.

Measurements of beta-activity on gummed film (e.g., Harley et al. 1960) can also be used to determine

the concentration of radioiodine locally. In this case, the loss of volatile nuclides during ashing must be accounted for as described in Beck (1984). The activity is then decay corrected to the time of sampling t using either Hicks decay-rate data (Hicks 1984) or the $t^{-1.2}$ approximation (see for example, Glasstone and Dolan 1977). The ground concentration is then calculated using the normalized deposition factors of Hicks (1984).

Scaling

Some attempts at scaling exposure by changes in distance from the test sites have been made in order to simplify assessment calculations for other locations. Such methods, often used in "ecologic" epidemiological studies, are normally a poor surrogate to location specific data. For example, simple estimation of thyroid dose for various atolls could be attempted by scaling downward the thyroid doses estimated at Rongelap by Lessard et al. (1985). Scaling factors could either be the ratio of respective distances to the two atolls or ratio of exposure-rates. Such methods likely yield poor results for at least two reasons. First, the mixture of short-lived radioiodines is intimately related to the transit time of the fallout cloud and the dynamics of decay are not linear. Exposure-rate decreases at early times much faster than the total radioiodine concentration in air. Second, the relative importance of the exposure-pathways may change with location because of local differences in lifestyle (e.g., degree of urbanization, etc.), but, more importantly, because of possible differences in the particle size distribution of local fallout. Finally, a factor frequently overlooked was that the Marshallese community of Rongelap and Ailinginae and the U.S. weathermen on Rongerik, for which detailed thyroid dose assessments have been made (Lessard et al. 1985; Klemm et al. 1986; Goetz et al. 1987), were evacuated relatively soon after the initial exposure.[8] Scaling thyroid doses from the Rongelapese to other communities, therefore, cannot be done with certainty, mainly because other communities (e.g., Likiep, Ailuk, Mejit, etc.) were not evacuated and subjected to decontamination, as were the Rongelapese. Although deposition was significantly lower at other locations, no efforts were made to minimize contamination of food, water, or eating utensils.

Measurement of ^{129}I

The availability of fallout times-of-arrival from the HASL fixed-instrument monitors enables the estimation of local concentrations of radioiodines immediately following deposition. For some locations and some events, there is little or poor historical data. In those cases, interpretation of other types of information may be necessary. In particular, the measurement of ^{129}I in the

local environment of each atoll (mainly soil) can possibly contribute to the understanding of the behavior of iodine in relation to other fission products. ^{129}I deposited in the Pacific region would have necessarily originated as global or local weapons test fallout; no other regional source existed. Thus, the geographic pattern of ^{129}I deposition (above a regional background value) may be used to ascertain the geographic pattern of local fallout and can be used to confirm the pattern of deposition suggested by the measurements of ^{137}Cs.

^{129}I measured in soil from a variety of locations within the U.S. has been shown to remain within the top 10 cm (Brauer and Strebin 1982) for several decades. Soil samples in 5 cm depth increments were obtained at locations across the Marshall Islands for the purpose of ^{129}I measurement. At this time, preparations of soil samples have begun using a caustic fusion preparation method[¶] followed by measurement by accelerator-based mass spectrometry (see Kilius et al. 1992).

Geographic pattern of thyroid disease prevalence as an indicator of exposure

Thyroid disease, both benign and malignant, is known to be caused by, among other things, exposure to ionizing radiation. In particular, the glands in the young are more radiosensitive to both disorders (Shore 1992; Wong et al. 1993). The occurrence of thyroid disease among the exposed Rongelap population has been well documented (see for example, Robbins and Adams 1989). The geographic pattern of prevalence rates has also been used as a surrogate indicator of exposure. For example, thyroid nodular disease was investigated and reported by Hamilton et al. (1987); they found the prevalence to be in excess of that expected among a non-exposed population and to decrease with increasing distance from Bikini. They concluded that fallout radioiodine exposure was more widespread than previously believed in the Marshall Islands and that it was the likely cause of those neoplasms. In the work of Hamilton et al. (1987), the prevalence rates of thyroid nodular disease in the Marshallese population nationwide were interpreted as a bioindicator of the possible exposure of the population. There are, of course, numerous difficulties in attempting to estimate the population exposure from prevalence rate data. In particular, the stochastic nature of disease occurrence is particularly apparent in small populations.

In an effort to verify the conclusions of Hamilton et al. (1987), and to further attempt to understand the radiological health effects over the entire Marshall Islands nation, a nationwide thyroid examination program using both palpation and high resolution ultrasound was begun in early 1993. At the time of this writing, over 6,500 Marshallese, including 4,000 over the age of 30 y, have been examined for thyroid abnormalities. Preliminary results (Simon et al. 1993b) indicate that the prevalence of nodules is at least as high as reported by

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[8] The 28 U.S. weatherman were evacuated from Rongerik in two groups, at 31 h and 36 h post shot. Sixteen Marshallese on Rongelap were evacuated by plane at 51 h post shot; another 48 were evacuated at the same time by ship. Eighteen Marshallese, temporarily resident on Sifo Island in Ailinginae Atoll were evacuated at 54 h post shot (Sharp and Chapman 1957).

Hamilton et al. (1987) and that thyroid cancer also appears to be in excess. Further study is underway for the purpose of making more definitive conclusions concerning the rates of disease. Dose reconstruction for Marshallese alive at the time of the atomic tests is necessary to determine the likelihood that those cases are truly a result of radiation exposure.

FINDINGS

This paper briefly presents two of the most recent results of dose assessment activities in the Marshall Islands: (1) summarizing the current radiological conditions at each atoll in terms of dose and (2) determining compliance of the radiological conditions at Rongelap with a dose action level for the purpose of providing guidance on resettlement.

The primary measurements from the NWRS were areal inventories (Bq m^{-2}) of ^{137}Cs in soil and specific activities (Bq kg^{-1}) in a variety of native foods. These measurement data have been coupled with the Rongelanese dietary description by Dignan et al. (1994) and used in stochastic dose calculations that simulate the variability of a number of parameters including plant uptake, spatial variation of exposure-rates over an island, and caloric intake rates among the population. Fig. 4 shows an example of the variation in predicted dose equivalent (external plus internal from ingestion of foods only) as a function of net in-situ count-rate of ^{137}Cs (as measured with a 40% HPGe detector at 1 m height). The linear relationship superimposed upon the predicted values give the approximate median value of the predicted dose as a function of count-rate: the dispersion of the points around the line is indicative of the uncertainty of the median dose.

The linear relationship between in-situ measured count-rates and internal dose was extended to all locations of the Marshall Islands as means to interpret environmental count-rates into estimates of dose. The predicted dose values pertain to unidentified individuals at each atoll that might adhere to the general dietary description of the assessment scenario. The location-specific environmental count-rates provided the scaling factor for each location. Units of dose, though not widely understood in a technical sense, can be compared among atolls and with international guidelines.

As an example, Fig. 5 presents present day median estimates of external plus internal dose (via ingestion of food products only) from ^{137}Cs on the islands of Bikini Atoll. These particular calculations assume a diet of 75% local food and 25% imported food (e.g., rice). It should be noted here that only one of the islands in Fig. 5 is actually inhabited today (Eneu island). Moreover, many of the other islands do not support sufficient food bearing plants to sustain a population. The assessment calculations in this figure are only intended as a tool to interpret environmental concentrations at each locations into a single consistent unit useful for comparison purposes by the Marshallese communities and government.

A second important application of a dose assessment in the Marshall Islands was to satisfy requirements of a
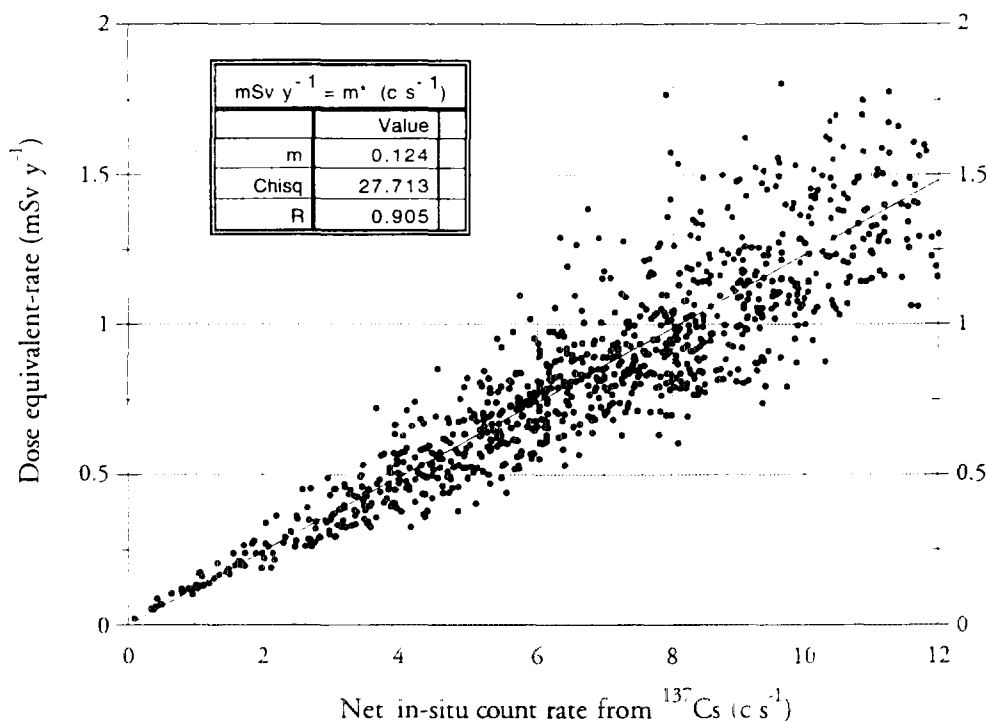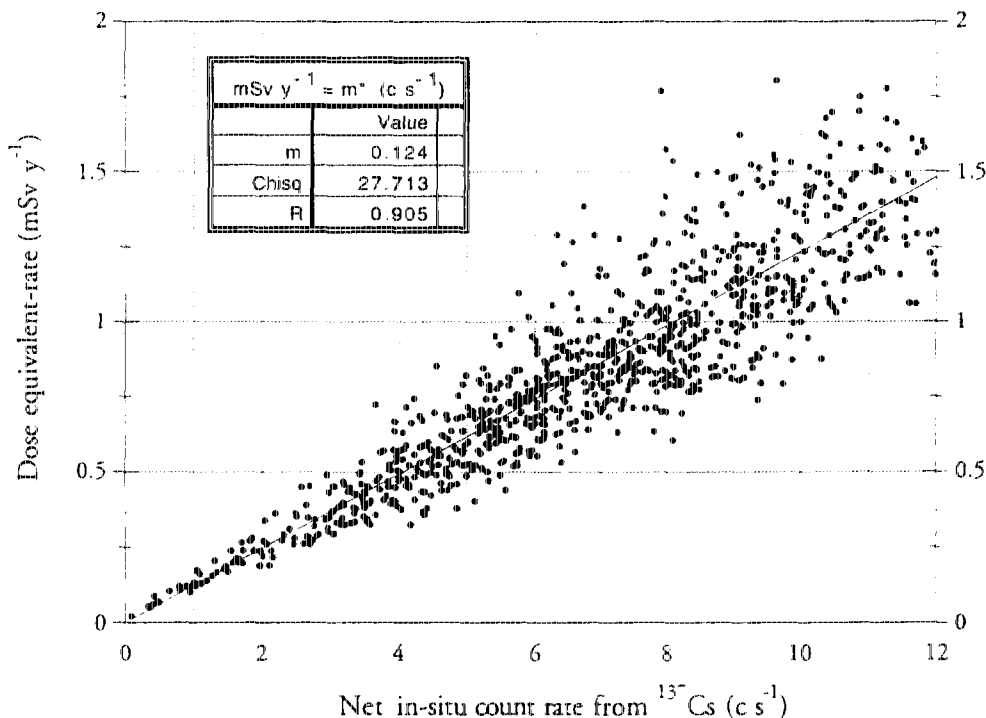

Fig. 4. Dose equivalent-rate (external + ingestion, mSv y^{-1}) as a function of net in-situ count-rate (c s^{-1}) from ^{137}Cs, determined from numerical simulations of local food diet.

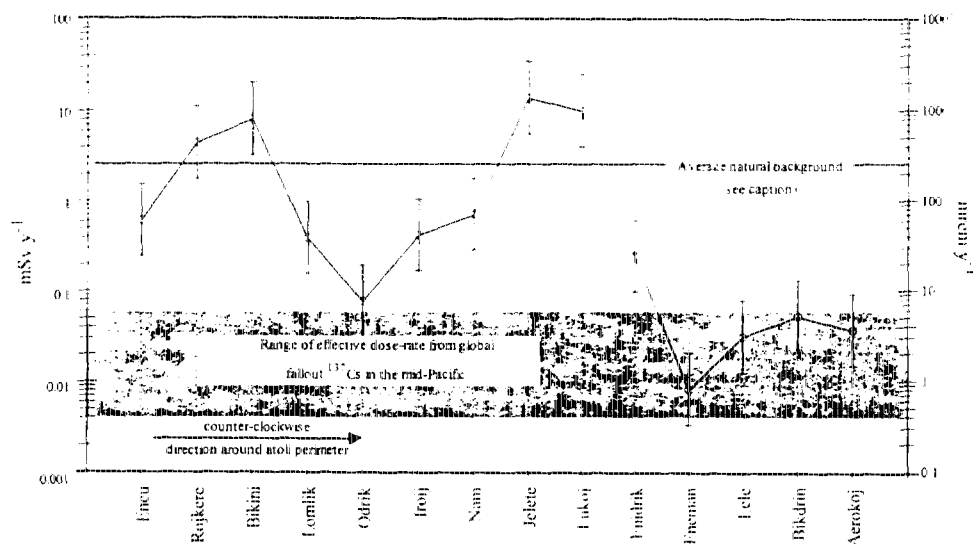Hamilton et al. (1987) and that thyroid cancer also appears to be in excess. Further study is underway for the purpose of making more definitive conclusions concerning the rates of disease. Dose reconstruction for Marshallese alive at the time of the atomic tests is necessary to determine the likelihood that those cases are truly a result of radiation exposure.

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A second important application of a dose assessment in the Marshall Islands was to satisfy requirements of a

Fig. 4. Dose equivalent-rate (external + ingestion, mSv y^{-1}) as a function of net *in-situ* count-rate (c s^{-1}) from ^{137}Cs, determined from numerical simulations of local food diet.

Fig. 5. External plus internal effective dose-rate (mSv y⁻¹ in 1995) from ¹³⁷Cs to unidentified adult on each of the islands of Bikini Atoll assuming a diet of 75% local food and 25% imported food (e.g., rice), see text for further information. Error bars express likely range of doses. Reference to natural background dose is Noshkin et al. (1994) and includes ^{210}Po and ^{210}Pb from seafood dietary sources.

four-way Memorandum of Understanding between the Marshall Islands and agencies of the U.S. (RMI/RAL-GOV/DOE/DOI 1992). In this application, compliance with an agreed upon dose action level was determined. The action level was defined such that all community members should not exceed 1 mSv y⁻¹ (above natural background) when consuming a diet of locally grown foods on Rongelap Island. Compliance was used to establish whether mitigation should be considered as a condition to resettle the island. Findings are shown here from calculations by Simon (1995) though similar assessments and conclusions were provided by NRC

Annual Effective Dose Equivalent from ^{137}Cs (mSv)
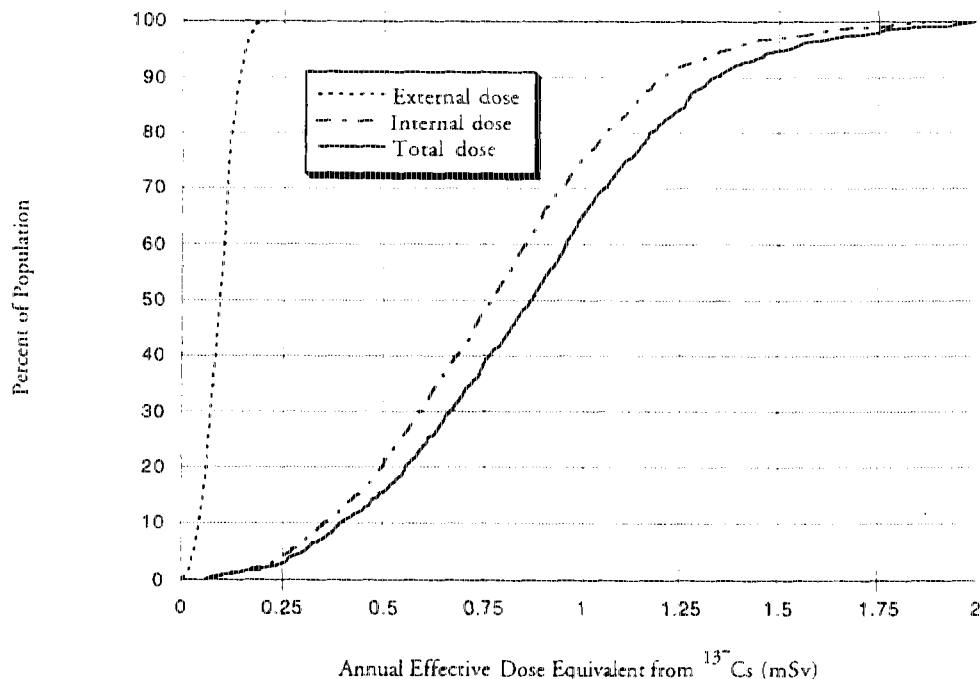
Fig. 6. Predicted distribution of doses among adult women who might inhabit Rongelap Island in 1995 and consume a diet of 75% locally produced food and 25% imported food (e.g., rice): annual effective dose equivalent from ^{137}Cs (mSv), sum of external exposure and internal dose-ingestion only), calculations by Monte-Carlo simulation.

(1994). Robison et al. (1994) and Thorne (1995). The results presented here are in the form of a cumulative population distribution of projected doses for adult women. In this example (Fig. 6), the variation of doses among the population mainly reflects the spatial variation of contamination on Rongelap Island, the variation of plant uptake, and the variation of caloric intake rates. Calculations indicate that about 35% of the women might exceed 1 mSv y^{-1}.

A response-surface was fitted to standardized partial regression correlation coefficients of the model input and out variables in a model sensitivity analysis. That analysis indicated that 80% of the variation in doses was due to the variation in environmental count-rate and caloric intake rates. Furthermore, the analysis indicated that 92% of the variation in doses could be accounted for by including the variation in plant:soil concentration ratios for the local food products jekeru, coconut cream, and pandanus.

CONCLUSIONS

Both retrospective and prospective dose assessments for inhabitants of the Marshall Islands necessarily encompass traditional dose assessment modeling techniques as well as relevant data for the environmental and cultural setting of the island nation. In the political and social context of the Marshall Islands, specifying relevant values for diet and lifestyle parameters for each atoll community as well as the age and sex distribution are key to credible assessments.

Utilizing recent environmental radiological measurements and an evaluation of various dietary alternatives, prospective assessments have been conducted recently for two different purposes. First, the annual dose from external exposure and ingestion of local foods has been projected for all islands of the RMI as a means to present a uniform and relatively easily understood metric that can be compared among locations and with international guidelines. Representative findings are presented for Bikini Atoll. Second, a prospective assessment for the population of Rongelap Island has been conducted using both traditional and current day diets. This exercise has provided information useful for determining compliance with an agreed upon dose action level and for advising community members on issues of safety and resettlement.

Dose reconstruction, on the other hand, has been extremely limited for Marshallese. Data requirements for radiological dose for dose reconstruction as opposed to present day dose assessment are more severe because of the rapid rate-of-change of the radionuclide mixture with time immediately after the test. Some historical data are available, however, for these purposes. Future dose reconstruction efforts will be for the purpose of radio-epidemiological analysis of the participants in a nation-wide thyroid disease study.

Dose assessment activities have highlighted the need for a comprehensive database of radiological infor-

mation and a mature understanding of lifestyle attributes. The radiological database must include location-specific radiological information—both current data and data obtained during the testing period are needed. Fortunately, both types of information are available for many locations.

The single most important conceptual requirement for conducting valid assessments is recognizing important exposure pathways. Attempts to quantify usual or unusual exposure pathways remain as contentious issues among scientists practicing risk assessment. One lesson learned repeatedly in Marshall Islands studies has been to rely on local expertise to provide information important to acquiring an understanding of pathways. No better information can be produced than that provided by the population whose quality of life is under examination.

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